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NONDIRECTIONAL BEACONS: COVERAGE LIMITATIONS DUE TO NIGHT EFFEC--ETC(U)
JUL 82 L A BERRY, M E JOHNSON

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Nondirectional Beacons: Coverage Limitations Due to Night Effect

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National Telecommunications and Information Administration
Institute for Telecommunications
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Final Report

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16. Abstract

Annex 10 of International Standards and Recommended Practices Aeronautical Telecommunications contains tables of the distances at which the groundwave and skywave from a non-directional beacon (NDB) are equal and the distances at which the groundwave exceeds the skywave by 10 dB. These tables were probably based upon the experience of users. In this report the modeling assumptions necessary to duplicate the tables using modern computer prediction methods are determined. A table of distances at which the groundwave exceeds the skywave by 10 dB is computed for frequencies from 190 kHz to 1000 kHz and for ground conductivities from 5 mho/m to 0.00025 mho/m.

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Form DOT F 1700.7 (8-72)

English/Metric Conversion Factors

Length

To / From	Cm	m	Km	in	ft	s mi	nmi
Cm	1	0.01	1×10^{-5}	0.3937	0.0328	6.21×10^{-6}	5.39×10^{-6}
m	100	1	0.001	39.37	3.281	0.0006	0.0005
Km	100,000	1000	1	39370	3281	0.6214	0.5395
in	2.540	0.0254	2.54×10^{-5}	1	0.0833	1.58×10^{-5}	1.37×10^{-5}
ft	30.48	0.3048	3.05×10^{-4}	12	1	1.89×10^{-4}	1.64×10^{-4}
S mi	160,900	1609	1.609	63360	5280	1	0.8688
nmi	185,200	1852	1.852	72930	6076	1.151	1

Area

To / From	Cm^2	m^2	Km^2	in^2	ft^2	S mi^2	nmi^2
Cm^2	1	0.0001	1×10^{-10}	0.1550	0.0011	3.86×10^{-11}	5.11×10^{-11}
m^2	10,000	1	1×10^{-6}	1550	10.76	3.86×10^{-7}	5.11×10^{-7}
Km^2	1×10^{10}	1×10^{6}	1	1.55×10^{9}	1.08×10^{7}	0.3861	0.2914
in^2	6.452	0.0006	6.45×10^{-10}	1	0.0069	2.49×10^{-10}	1.88×10^{-10}
ft^2	929.0	0.0929	9.29×10^{-8}	144	1	3.59×10^{-8}	2.71×10^{-8}
S mi^2	2.59×10^{10}	2.59×10^{6}	2.590	4.01×10^{9}	2.79×10^{7}	1	0.7548
nmi^2	3.43×10^{10}	3.43×10^{6}	3.432	5.31×10^{9}	3.70×10^{7}	1.325	1

Volume

To / From	Cm^3	Liter	m^3	in^3	ft^3	yd^3	fl oz	fl pt	fl qt	gal
Cm^3	1	0.001	1×10^{-6}	0.0610	3.53×10^{-5}	1.31×10^{-6}	0.0338	0.0021	0.0010	0.0002
liter	1000	1	0.001	61.02	0.0353	0.0013	33.81	2.113	1.057	0.2642
m^2	1×10^{6}	1000	1	61,000	35.31	1.308	33,800	2113	1057	264.2
in^3	16.39	0.0163	1.64×10^{-5}	1	0.0006	2.14×10^{-5}	0.5541	0.0346	2113	0.0043
ft^3	28,300	28.32	0.0283	1728	1	0.0370	957.5	59.84	0.0173	7.481
yd^3	765,000	764.5	0.7646	46700	27	1	25900	1616	807.9	202.0
fl oz	29.57	0.2957	2.96×10^{-5}	1.805	0.0010	3.87×10^{-5}	1	0.0625	0.0312	0.0078
fl pt	473.2	0.4732	0.0005	28.88	0.0167	0.0006	16	1	0.5000	0.1250
fl qt	946.3	0.9463	0.0009	57.75	0.0334	0.0012	32	2	1	0.2500
gal	3785	3.785	0.0038	231.0	0.1337	0.0050	128	8	4	1

Mass

To / From	g	Kg	oz	lb	ton
g	1	0.001	0.0353	0.0022	1.10×10^{-6}
Kg	1000	1	35.27	2.205	0.0011
oz	28.35	0.0283	1	0.0625	3.12×10^{-5}
lb	453.6	0.4536	16	1	0.0005
ton	907,000	907.2	32,000	2000	1

Temperature

$^{o}C = 9/5\ (^{o}F - 32)$

$^{o}F = 5/9\ (^{o}C) + 32$

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NONDIRECTIONAL BEACONS:

COVERAGE LIMITATIONS DUE TO NIGHT EFFECT

L. A. Berry and M. E. Johnson*

1. INTRODUCTION

Paragraph 6.3.4 of Aeronautical Telecommunications [8] Annex 10 begins:

(a) The distances at night at which the groundwave and skywave components of the received field are likely to be equal are as follows:

Frequency	Over Land	Over Sea
200 kHz	500 km	550 km
300 kHz	390 km	520 km
400 kHz	310 km	500 km

(b) The distances at night at which the groundwave component of the received field is likely to exceed the skywave component by 10 dB are as follows:

Frequency	Over Land	Over Sea
200 kHz	300 km	320 km
300 kHz	230 km	300 km
400 kHz	200 km	280 km

In this context, "groundwave" refers to radio energy that travels from transmitter to receiver without reflection from the ionosphere; "skywave" refers to energy reflected from the ionosphere. At night, the skywave may be strong enough to cause an erroneous bearing indication in a direction-finding receiver. This problem is called the "night effect."

The frequency dependence of the tables is not entirely consistent with that of International Radio Consultative Committee (CCIR) propagation prediction

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methods. This difference is shown and discussed in Section 2. The discrepancy between a table produced using CCIR prediction methods and the table in Annex 10 is probably smaller than the expected accuracy of the table and is certainly smaller than the variability of the nighttime low- and medium-frequency skywave. So CCIR prediction methods can be used to extend the table to different ground conductivities and to a larger range of frequencies.

Section 3 of this report describes the propagation prediction methods used to produce an extended table. The input parameters used in the methods are listed and justified. A table of distances at which the received groundwave component exceeds the skywave component by 10 dB for 90 percent of the time for intermediate solar cycle conditions is produced.

2. REPRODUCING THE CURRENT TABLES

The computer program used to compute LF groundwave and skywave propagation was based on the program LF SNR, described by Berry [1] (unpublished OT Technical Memorandum 78-247). However, the program was modified in two ways:

First, the CCIR groundwave program [4,5] was substituted for the classical groundwave subroutine described by Berry. In classical groundwave propagation theory, the earth is assumed to be a smooth sphere surrounded by free space. The refractive influence of the earth's atmosphere is approximated by using an "effective earth's radius," which is an accurate approximation if the index of refraction of the atmosphere varies linearly with height [2].

The CCIR groundwave program is based on a method developed by Rotheram [9]. The methods are applicable to a refractive index that has an arbitrary variation with height, but in this report, an exponential variation with height is assumed [5]. The CCIR program was modified to be a subroutine for the existing low-frequency (LF) propagation program. Vertical polarization was assumed.

There are two CCIR reports containing skywave propagation prediction methods for the frequency range of interest. CCIR Report 435-3 (Mod F), "Prediction of Sky-Wave Field Strength Between 150 and 1600 kHz," [7] was developed to predict interference in the MF broadcasting service. It is an empirical method that includes the effects of latitude, time, magnetic azimuth of propagation, season, and sunspot number. Unfortunately, the methods were developed primarily for long paths (more than 500 km). The report shows skywave field strength calculations for paths as short as 300 km, but (as later discussion will show) the curves are

surely inaccurate at these distances. Reference to the table in (b) of the Introduction (from Annex 10) shows that almost all the distances of interest in non-directional beacon (NDB) night effect are less than 300 km. Therefore, the methods of CCIR Report 435-3 cannot be used for our purposes.

CCIR Report 265 [3,6] provides skywave propagation prediction methods for frequencies from about "30 kHz to about 500 kHz." In fact, at short distances, the methods can be used up to about 1000 kHz. Furthermore, the available computer program used the skywave reflection coefficients in Report 265-2 [3].

As the second modification of the existing program, the ionospheric reflection coefficients were varied in successive runs until the tables in Annex 10 were reproduced. Tables 1 and 2 show the results.

Table 1. Computed Groundwave (GW) Field Strength (dBu) Minus Computed Skywave (SW) Field Strength (dBu) at the Distances Shown
(The skywave was computed using the reflection coefficients in Fig. 1.)

Over Land			Over Sea	
Frequency	Distance	GW-SW	Distance	GW-SW
200 kHz	500 km	-0.2	550 km	0.0
300 kHz	390 km	-0.4	520 km	0.0
400 kHz	310 km	+0.2	500 km	0.0

Table 2. Computed Groundwave (GW) Field Strength (dBu) Minus Computed Skywave (SW) Field Strength (dBu) at the Distances Shown
(The skywave was computed with the reflection coefficients shown in Fig. 1.)

Over Land			Over Sea	
Frequency	Distance	GW-SW	Distance	GW-SW
200 kHz	300 km	10.0	320 km	10.3
300 kHz	230 km	10.1	300 km	9.9
400 kHz	200 km	10.0	280 km	9.9

The precision in the original tables probably was no better than 1 dB (error tolerance of ±0.5 dB) or 10 km (error tolerance of ±5 km); so the calculations "duplicate" the Annex 10 tables because the largest difference is 0.4 dB. Further adjustment of the ionospheric reflection coefficients probably would make Tables 1 and 2 even closer to those in Annex 10, but such refinement would serve no practical purpose.

Now we will consider how well the ionospheric reflection coefficients inferred from the tables in Annex 10 agree with other observations.

Figure 1 shows the reflection coefficients used to fit the tables. (Figures are grouped at the end of the text.) Angles of incidence smaller than 40 degrees and larger than 70 degrees had no effect on the skywave at the distances in the tables, so that linear extrapolation was used to complete the curves. However, values outside the range 40 to 70 degrees should not be considered to be accurate.

In Figure 2, the fitted reflection coefficients are converted to reflection loss and are compared to reflection coefficents derived from CCIR Report 265-2 [3], which gives two sets of nighttime reflection coefficients--one set for solar cycle minimum and one set for solar cycle maximum. These two sets were averaged to get reflection coefficients for average solar cycle conditions. Both the fitted reflection loss and the empirical loss from CCIR Report 265-2 decrease with increasing angle of incidence. However, the CCIR reflection loss increases with frequency in this frequency range. For the important angles of incidence smaller than 70 degrees, the fitted reflection loss at 300 kHz is less than that at 200 kHz. And the loss at 300 kHz is the same as that at 400 kHz. Finally, notice that the fitted reflection loss is less than the CCIR loss for the important angles of incidence between 30 and 70 degrees. At the middle frequency, the difference is about 6 dB.

This 6-dB difference gives a clue about the derivation of the tables in Annex 10. The reflection coefficients in CCIR Report 265-2 are average, or median, values. The distance from the median field strength to the ninetieth percentile is about 6.5 dB [7]. It would seem reasonable to protect NDB's from self-interference more than 50% of the time. Perhaps the tables in Annex 10 were intended to provide protection 90% of the time. At least, reflection coefficients from CCIR Report 265-2, increased by 6.5 dB to provide protection from interference 90% of the time, would provide tables that approximate those in Annex 10, and that could be extended in frequency. The next section describes such calculations.

3. CALCULATIONS OF AN EXPANDED TABLE

The CCIR groundwave model was used to compute the groundwave component of the field strength [4,5]. An exponential variation of atmospheric refractivity was assumed. In particular, it was assumed that the refractive index of the atmosphere at height h above the surface is given by

$$\text{refractive index} = 1. + (N_S)\exp(-h/H)10^{-6} \quad ,$$

where $N_S = 300$ and the scale height $H = 8$ km. These values are appropriate for a "standard atmosphere." The relative dielectric constant of the ground was set equal to 4, and the conductivity varied from 0.00025 mho/m to 0.03 mho/m for land paths. For sea paths, the relative dielectric constant of 80 was used, and the conductivity was set equal to 5 mho/m.

CCIR Report 265-2 gives two sets of nighttime ionospheric reflection coefficients--one for solar cycle minimum conditions and one for solar cycle maximum conditions. To achieve typical solar cycle conditions, the reflection coefficients for minimum and maximum conditions were averaged. Then 6.5 dB was subtracted from this reflection loss to protect the NDB's from interference 90% of the time, as discussed in Section 2. The resulting reflection loss is shown in Figures 3, 4, and 5 for frequencies of 200 kHz, 500 kHz, and 1000 kHz, respectively. Notice that no reflection loss is given for the smaller angles of incidence at 1000 kHz. These angles correspond to shorter path lengths and limit the calculation of the distance at which the groundwave is 10 dB stronger than the skywave at this frequency.

Figures 6-8 show the strength of the groundwave and skywave components of the field strength for sea water paths. Figure 6 is for a frequency of 200 kHz. The groundwave component decreases smoothly with increasing distance. The skywave component is much smaller than the groundwave at short distances, then increases to a broad maximum. Although not shown in Figure 6, the skywave component also decreases with increasing distance at larger distances.

Figure 7 shows the components for 500 kHz for sea paths. Both the groundwave component and the skywave component are smaller at large distances for the higher frequency, so that the distance at which the two components are equal is about the same as for 200 kHz. This does not agree with the tables in Annex 10 (see Section 1), which show the components equal at a shorter distance for the higher frequency than for the lower frequency. If the skywave component were just two

decibels stronger at 500 kHz, the crossover point would have the same frequency dependence as in Annex 10. This shows how an inaccuracy in reflection loss that is small compared with its variability can change the crossover distance by a large amount and indicates that distances in the tables should not be interpreted as fixed and accurate.

Figure 8 shows the groundwave and skywave components propagating over sea water for a frequency of 1000 kHz. The skywave component is nearly as strong as it is for 500 kHz, but the groundwave component is weaker; so the distance at which they are equal is shorter than at 500 kHz.

Figures 9-11 show the same calculations as Figures 6-8 except that the ground conductivity is 0.004 mho/m, representative of poorly conducting soil. In Figure 9, for a frequency of 200 kHz, the skywave component is slightly weaker than it is in Figure 6 (sea path) because of the smaller ground reflection coefficient in the foreground of the antenna. However, the groundwave component attenuates much faster than before because it is propagating over poorly conducting soil. Therefore, the two components are equal at a much shorter distance.

The same thing is true for 500 kHz, as shown in Figure 10, and for 1000 kHz, as shown in Figure 11. Indeed, the two 1000-kHz components are equal at such a short distance, that the skywave could not be reliably computed (because no reflection coefficents are available).

CCIR Report 265 [3,6] does not show seasonal variation for the nighttime reflection coefficients, even though CCIR Report 435-3 [7] does. Therefore, it is assumed that the reflection coefficients are for "average" (perhaps equinox) seasonal conditions. Futhermore, the reflection coefficients in Report 265-2 have no latitudinal or time variation. It is assumed that they are for midlatitude and midnight.

Table 3 shows the distances at which the groundwave is computed to be 10 dB stronger than the skywave for these assumed conditions as a function of frequency and ground conductivity. The CCIR groundwave model has two branches--one which assumes a spherical earth and one which assumes a flat earth [5,9]. The spherical earth model was used whenever possible. When it failed, the flat earth model was used. Distances computed with the flat earth model are marked with an asterisk in Table 3.

No empirical reflection coefficients were available for the shorter distances at frequencies above 700 kHz, so some elements in Table 3 are empty.

There are two notable features in Table 3. First, for any given frequency, the distance at which the groundwave exceeds the skywave by 10 dB decreases with decreasing conductivity. This is because the skywave is only slightly affected by the ground conductivity, while the groundwave attenuates more quickly when propagating over poorly conducting soil.

Second, except for the two highest ground conductivities, the cross-over distance decreases as the frequency increases. Again, the groundwave component is more sensitive to frequency than the skywave component. For the two highest ground conductivities, the frequency dependence is more complicated. This results in the major difference between Table 3 and the tables in Annex 10. In Annex 10, the distance at which the groundwave component exceeds the skywave component decreases with frequency for both sea paths and land paths. In Table 3, this distance increases with frequency for sea paths (and also for a ground conductivity of 0.03 mho/m) for the lower frequencies.

The distances in Table 3 imply a precision of 1 km and are the distances at which the groundwave component minus the skywave component is 10, ±0.1 dB. However, the skywave is quite variable. The distance from the median field to the upper decile is 6.4 dB [7]. As shown earlier when discussing Figures 6-9, a difference of only 2 dB can change the cross-over distance by tens of kilometers. On a particular night, the actual distance at which the groundwave exceeds the skywave by 10 dB might be different from that shown in the table by 10%. The distances in the table are the best estimates that can be made using available international propagation prediction techniques.

4. CONCLUSIONS

The distances at which the groundwave component of the field of a non-directional beacon is 10 dB stronger than the skywave component for 90 percent of the time have been computed using CCIR propagation prediction techniques. The distances are presented in Table 3 for frequencies from 190 kHz to 1000 kHz and for ground conductivities from 0.00025 mho/m to 5 mho/m. Table 3 differs from similar tables in Annex 10 by amounts that are probably within variation caused by the uncertainty in the calculation of the low- and medium-frequency ionosperic reflection loss.

Table 3. Distance in Kilometers at Which the Groundwave is 10 dB Greater than the Skywave

Frequency in kHz	Ground Constants								
	ε=80	ε=4	ε=4	ε=4	ε=4	ε=4	ε=4	ε=4	ε=4
					mho/m				
	σ=5	σ=.030	σ=.015	σ=.008	σ=.004	σ=.002	σ=.001	σ=.0005	σ=.00025
190	275	273	265	250	225	192	155	122	98*
200	280	275	265	250	223	188	150	118	95*
250	290	280	263	240	205	167	131	103	84*
300	295	280	257	228	187	149	115	93	77*
350	300	275	245	212	170	133	103	84*	71*
400	305	265	233	197	155	121	94	77*	67*
450	305	255	220	182	142	110	88	73*	63*
500	305	245	207	168	131	102	82	68*	60*
535	303	237	197	160	124	96	78	66*	58*
600	300	223	183	147	113	88	72	61*	54*
700	293	202	161	128	98	78	64*	55*	49*
800	285	180	140	110	85	68	57*	49*	--
900	275	160	---	---	---	---	---	---	--
1000	260	148	---	---	---	---	---	---	--

*Flat earth.

5. REFERENCES

[1] Berry, L. A. (1964), Wave hop theory of long distance propagation of low-frequency radio waves, RADIO SCIENCE, Vol. 68D, No. 12, pp. 1275-1284.

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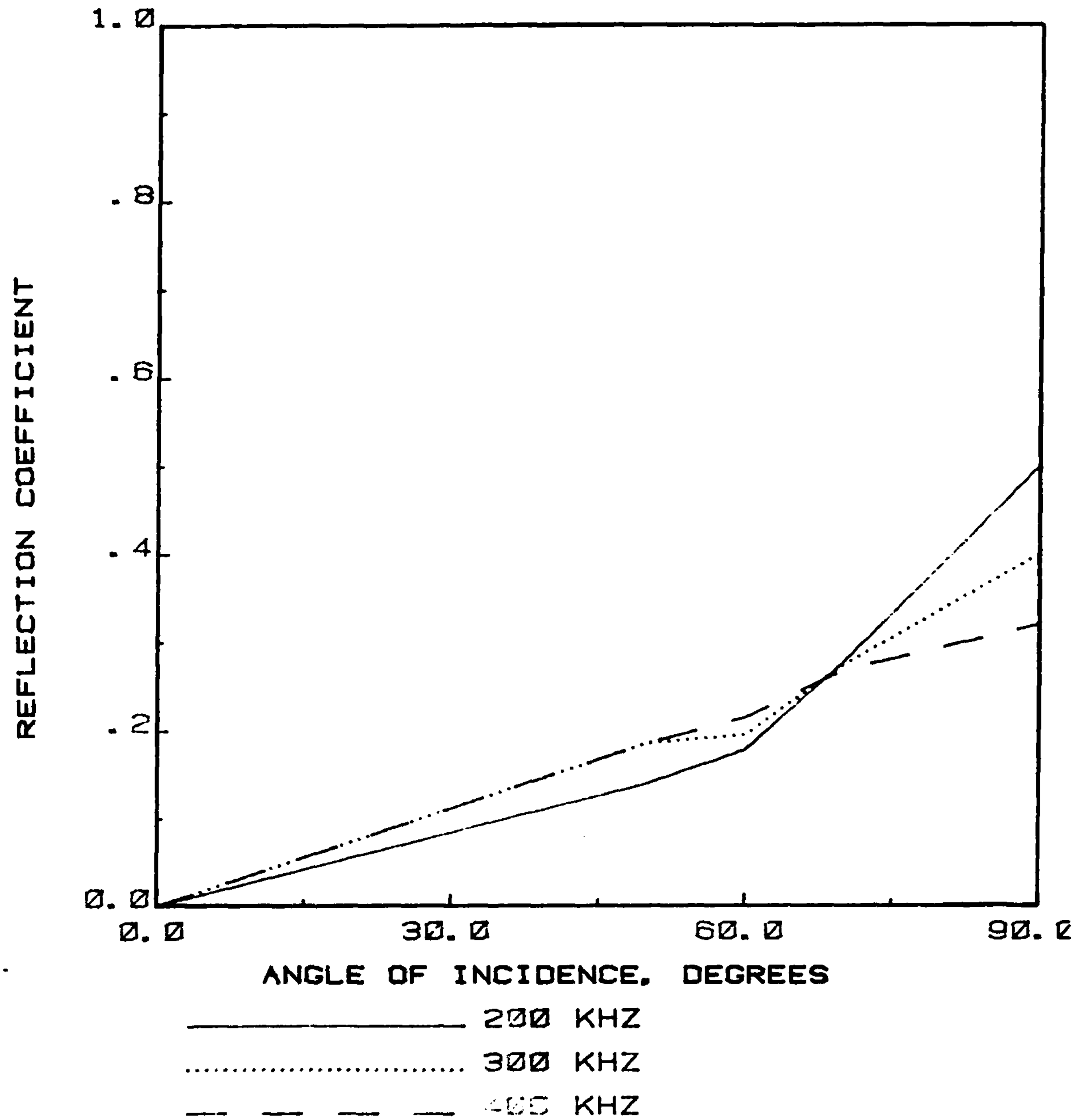

Figure 1. Ionospheric reflection coefficients required to compute the same distances as are in Annex 10, para. 6.3.4. The values from 0-40° and 70-90° are extrapolations.

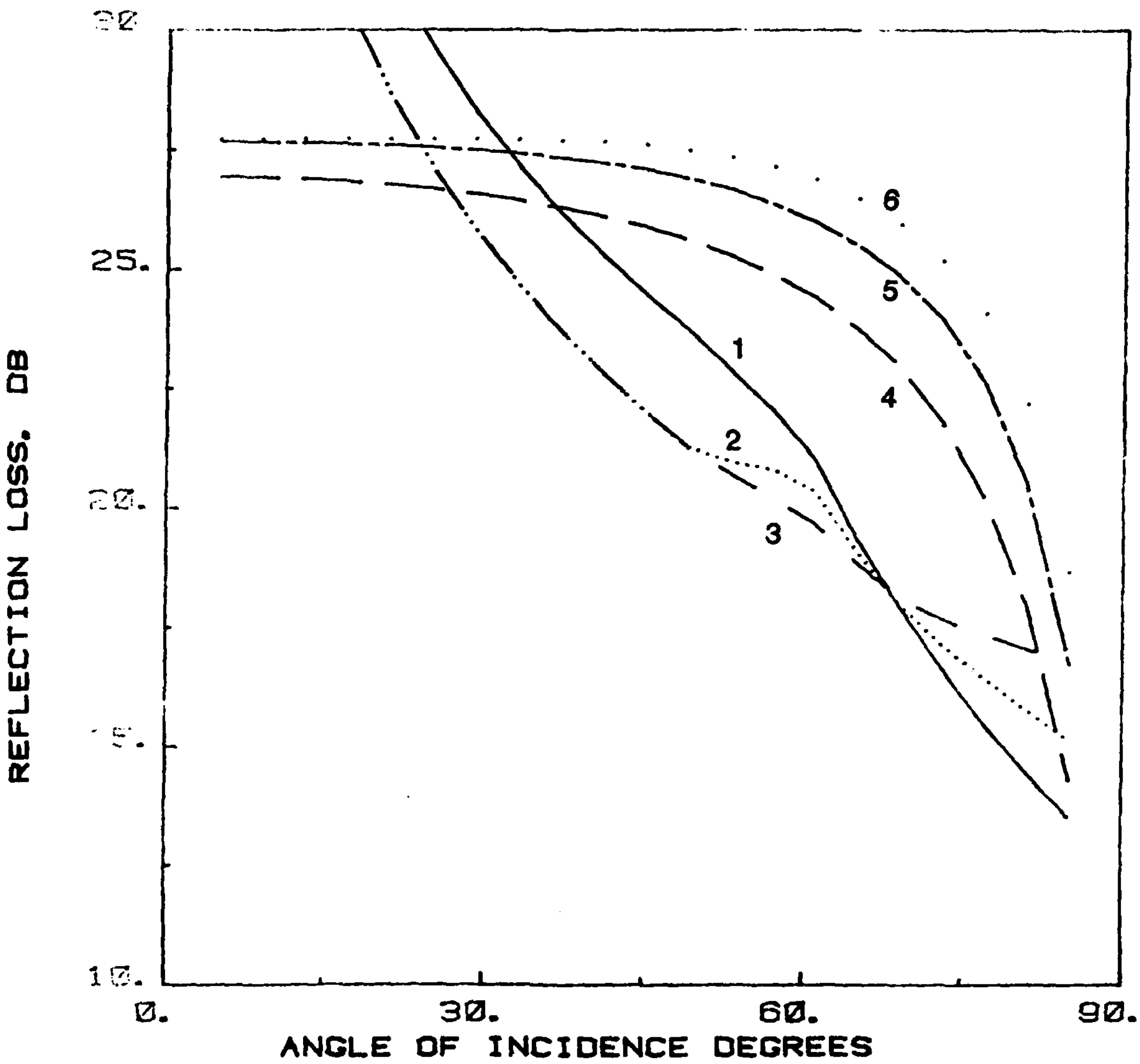

Figure 2. Comparison of the reflection loss required to fit the tables in Annex 10 and reflection loss from CCIR Report 265-2. Curves 1, 2, and 3 are the reflection coefficients from Figure 1 for 200, 300, and 400 kHz, respectively. Curves 4, 5, and 6 are based on CCIR Report 265-2 for 200, 300, and 400 kHz, respec-ively.

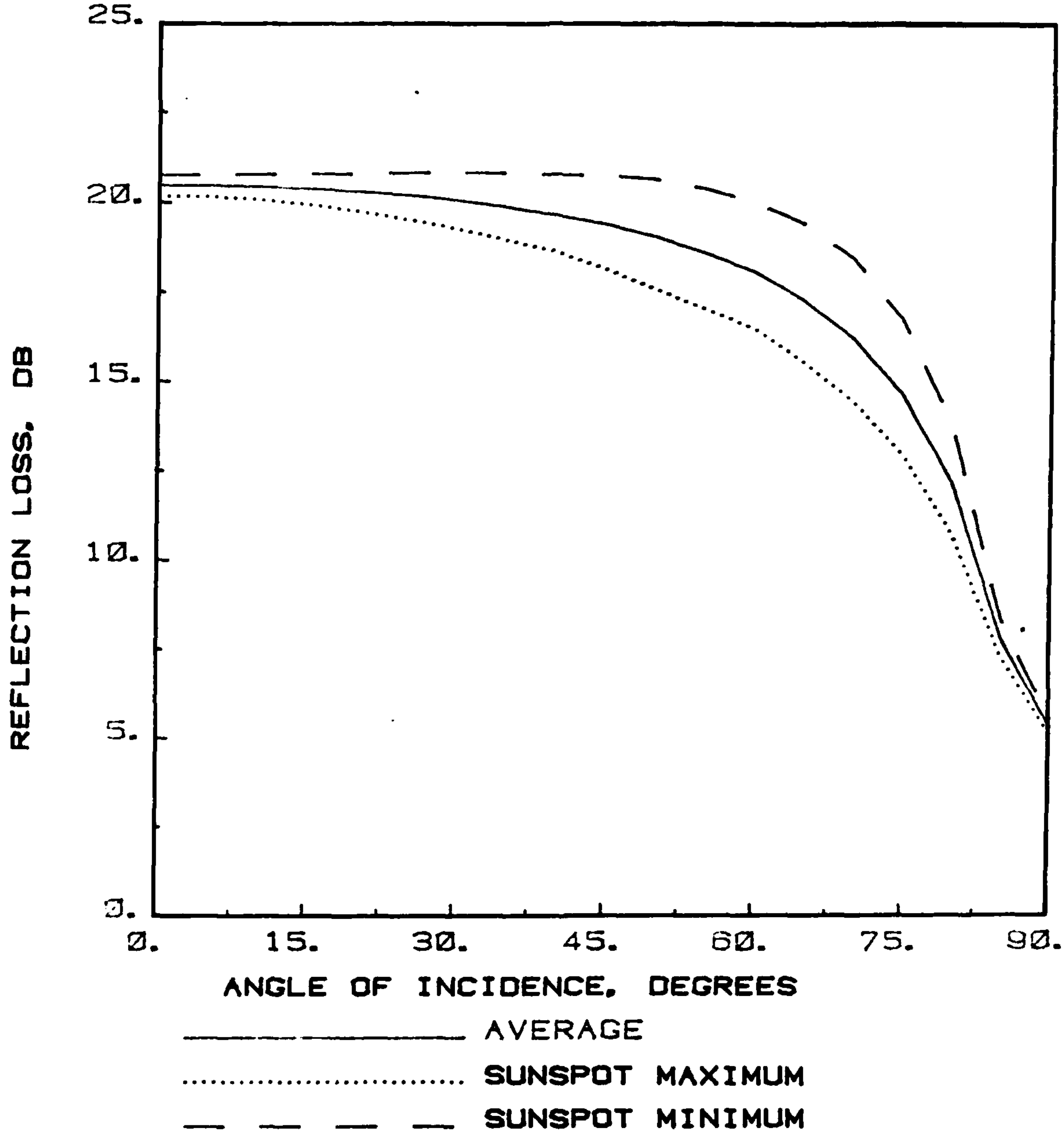

Figure 3. Ionospheric reflection loss for 200 kHz at night (from CCIR Report 265).

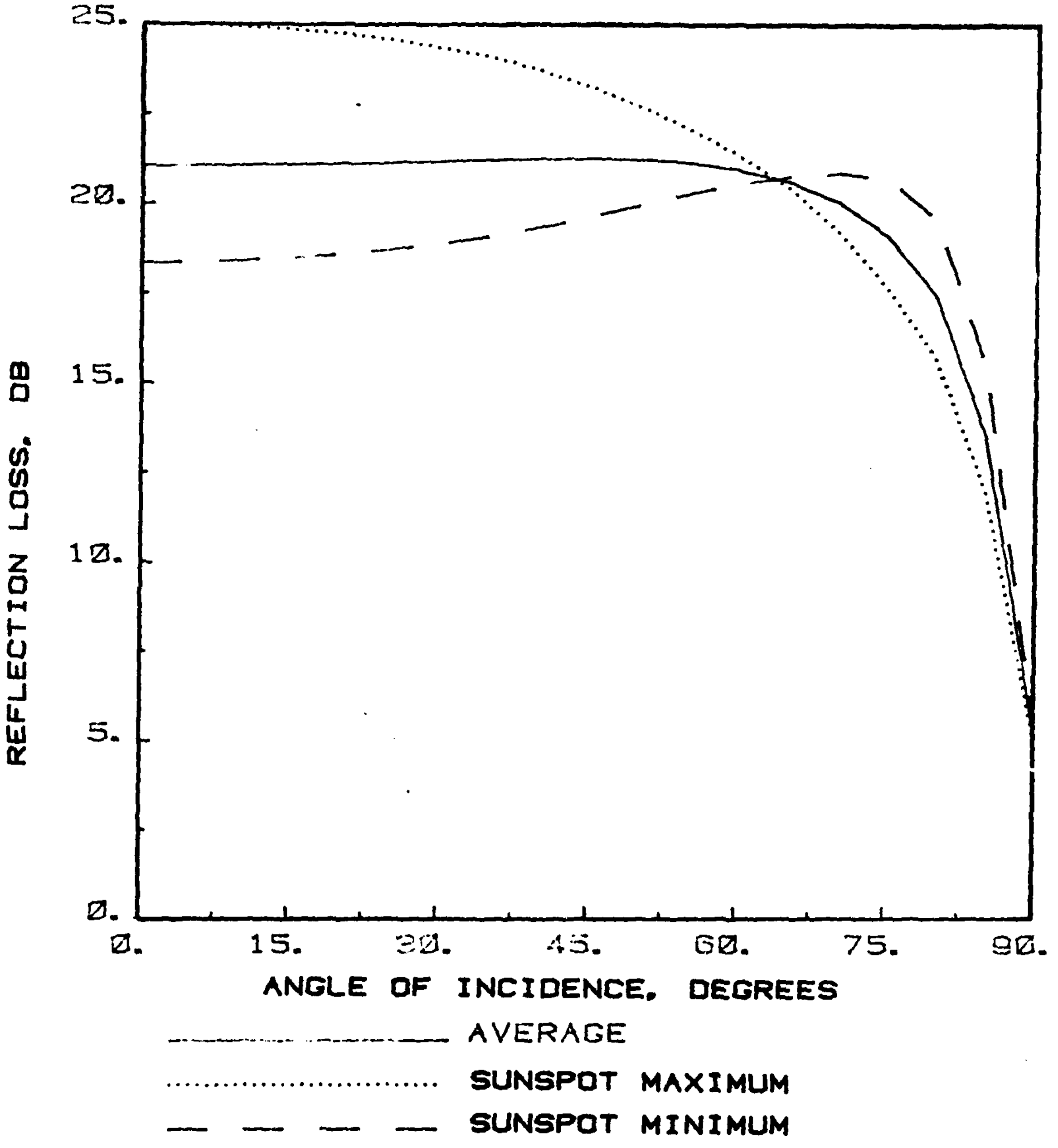

Figure 4. Ionospheric reflection loss for 500 kHz at night (from CCIR Report 265).

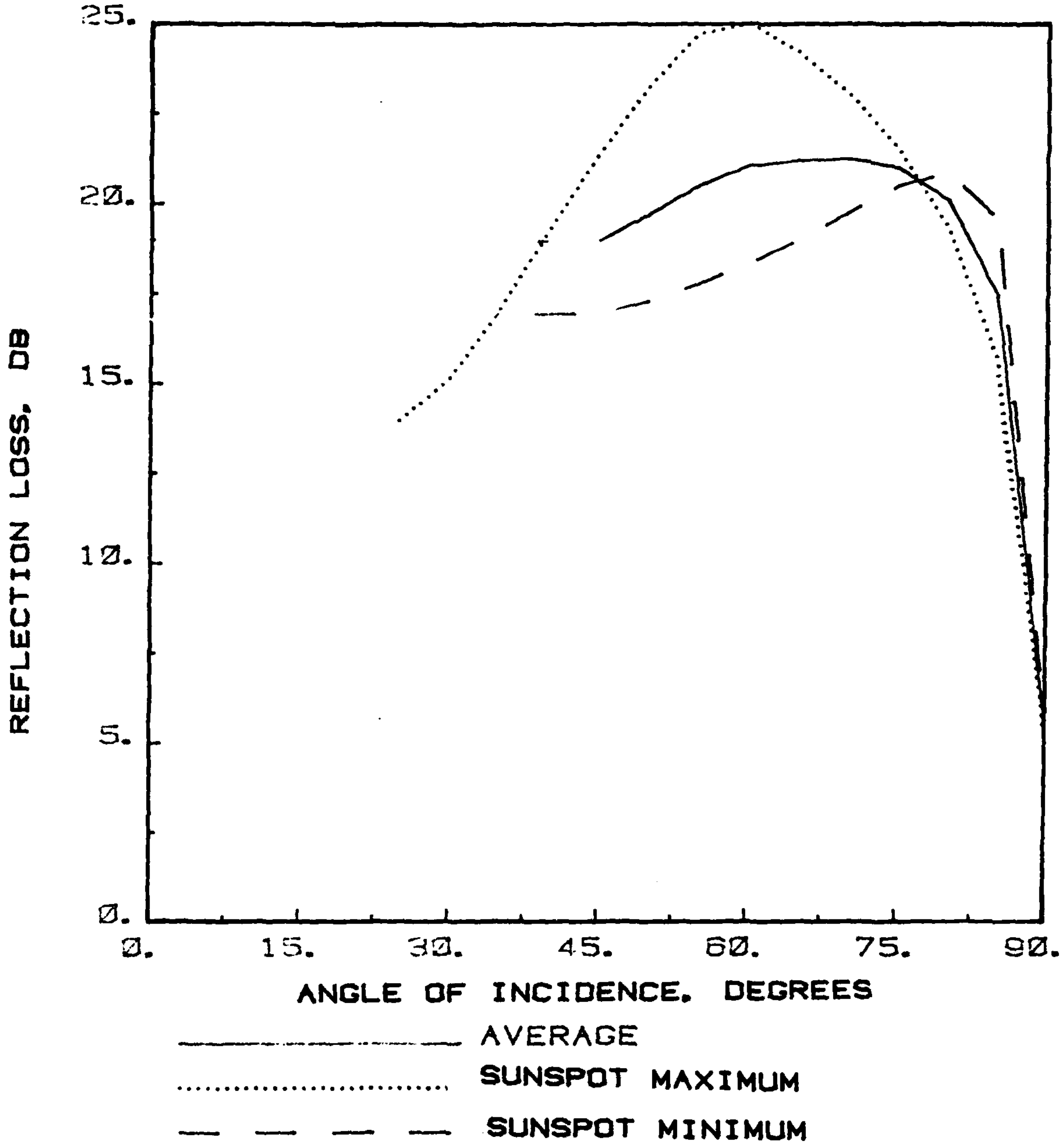

Figure 5. Ionospheric reflection loss for 1000 kHz at night (from CCIR Report 265). No data are given for angles of incidence smaller than 45° at sunspot minimum or smaller than 30° at sunspot maximum.

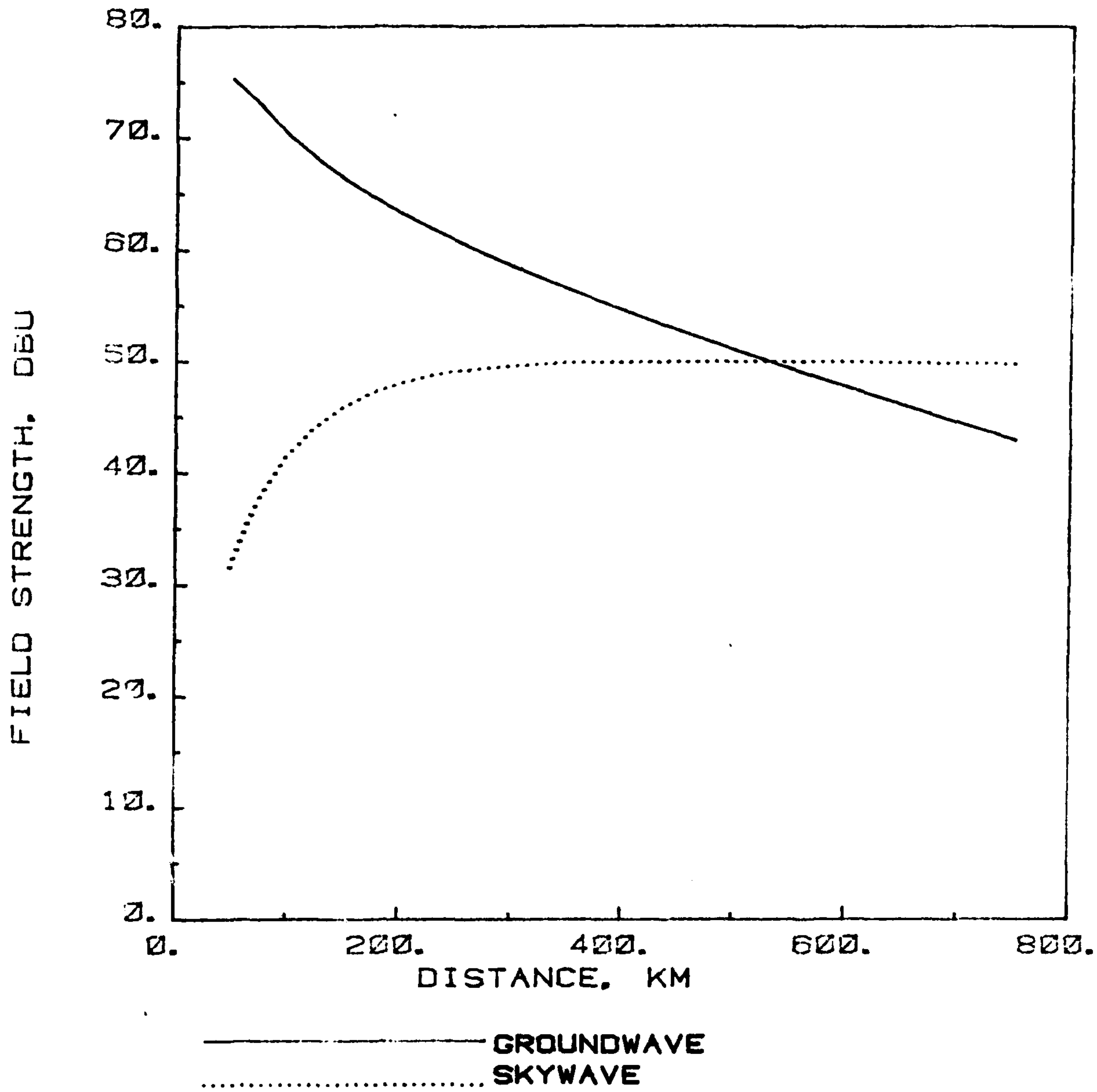

Figure 6. Groundwave and skywave components of the field strength as a function of distance for 200 kHz over sea paths.

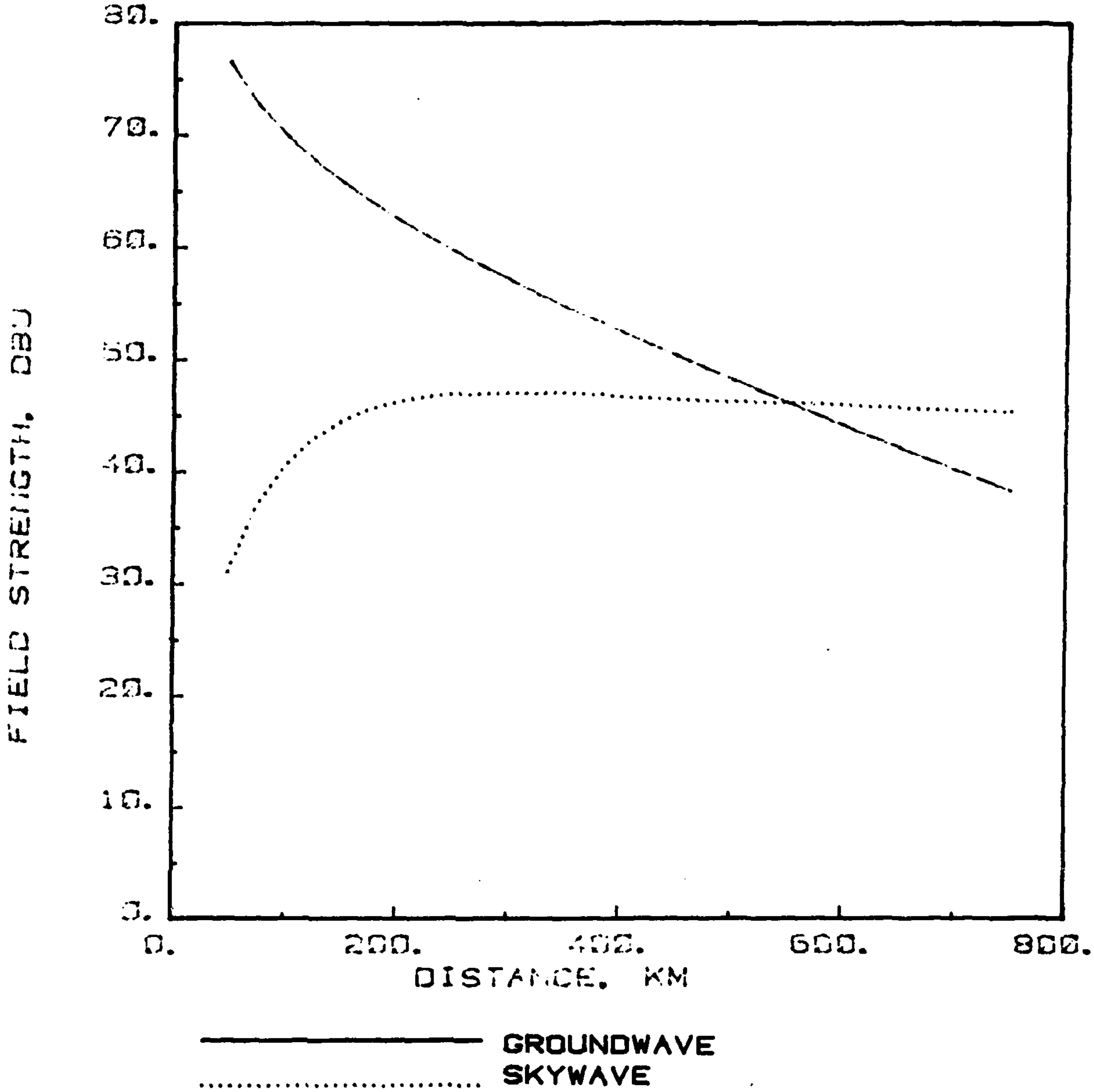

Figure 7. Groundwave and skywave components of the field strength as a function of distance for 500 kHz over sea paths.

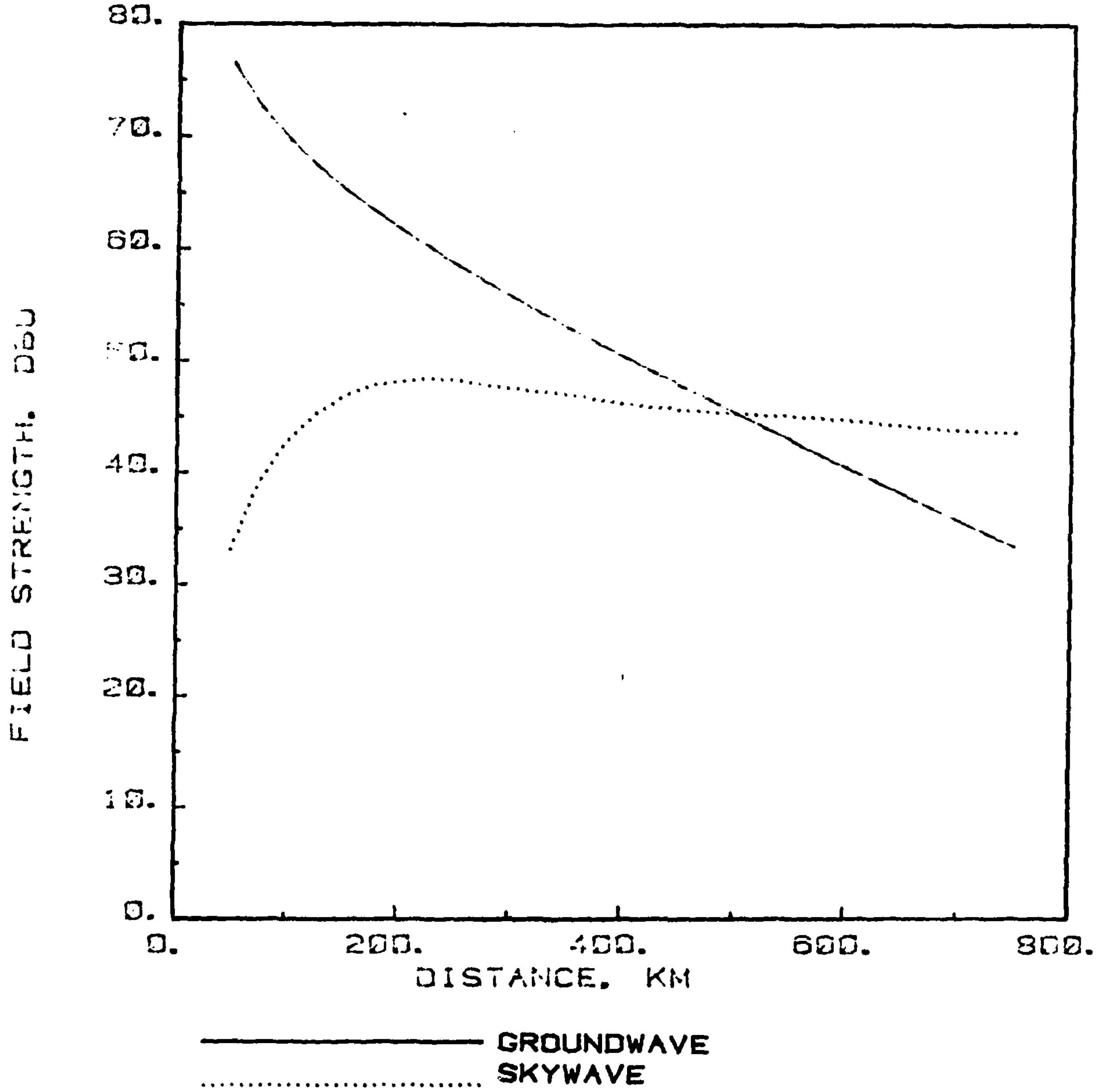

Figure 8. Groundwave and skywave components of the field strength as a function of distance for 1000 kHz over sea paths.

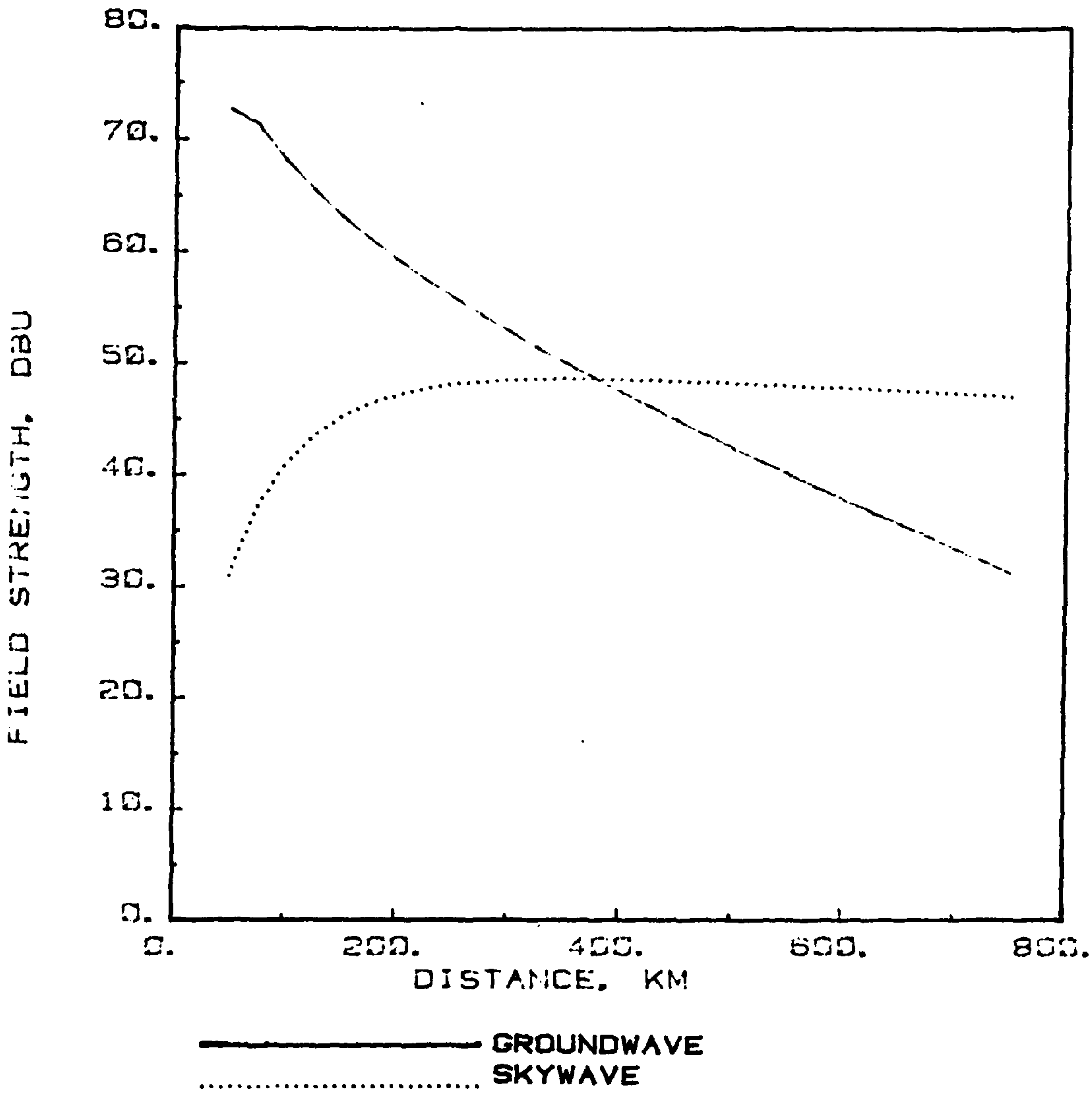

Figure 9. Groundwave and skywave components of the field strength as a function of distance for 200 kHz over land paths.

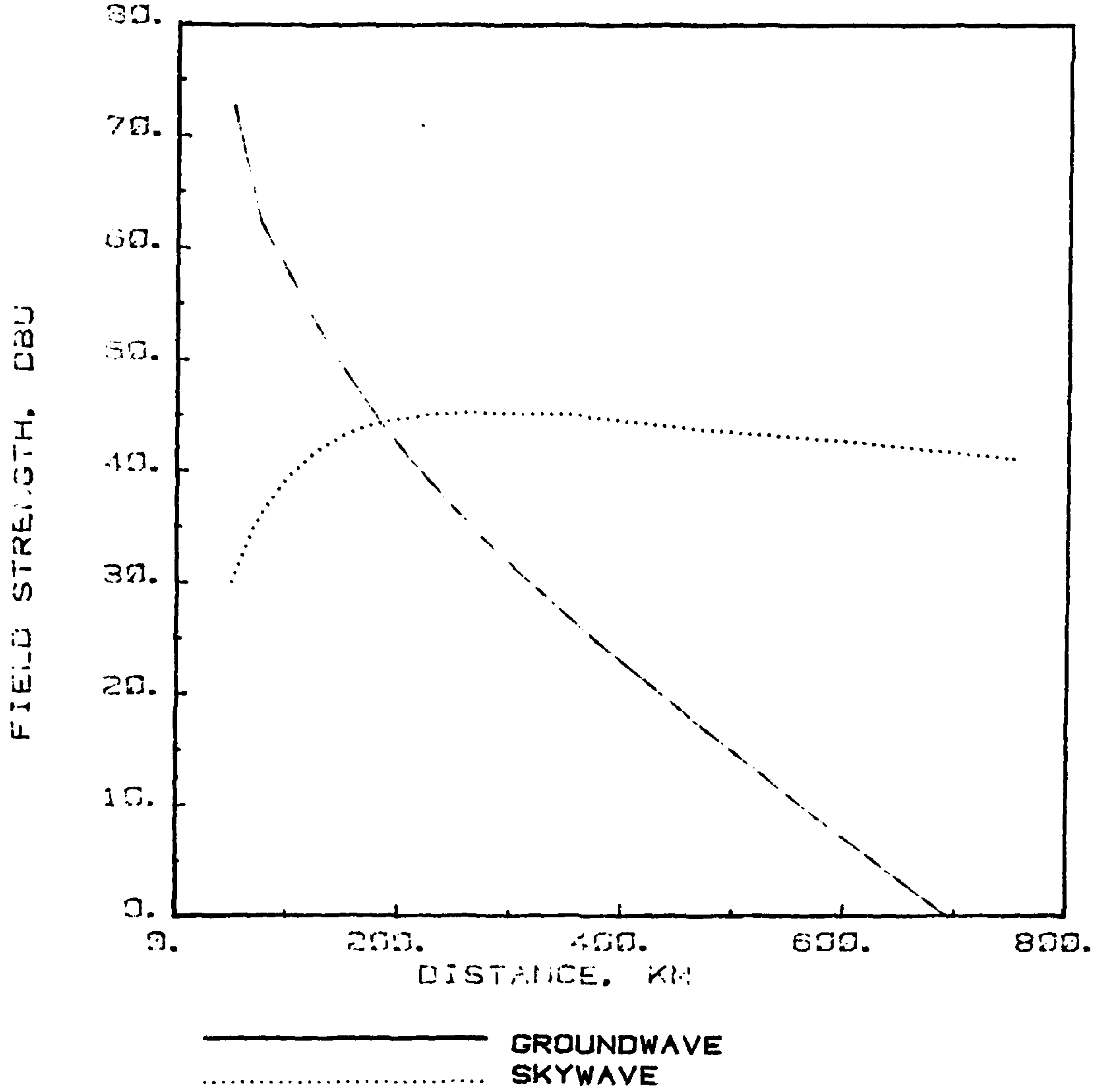

Figure 10. Groundwave and skywave components of the field strength as a function of distance for 500 kHz over land paths.

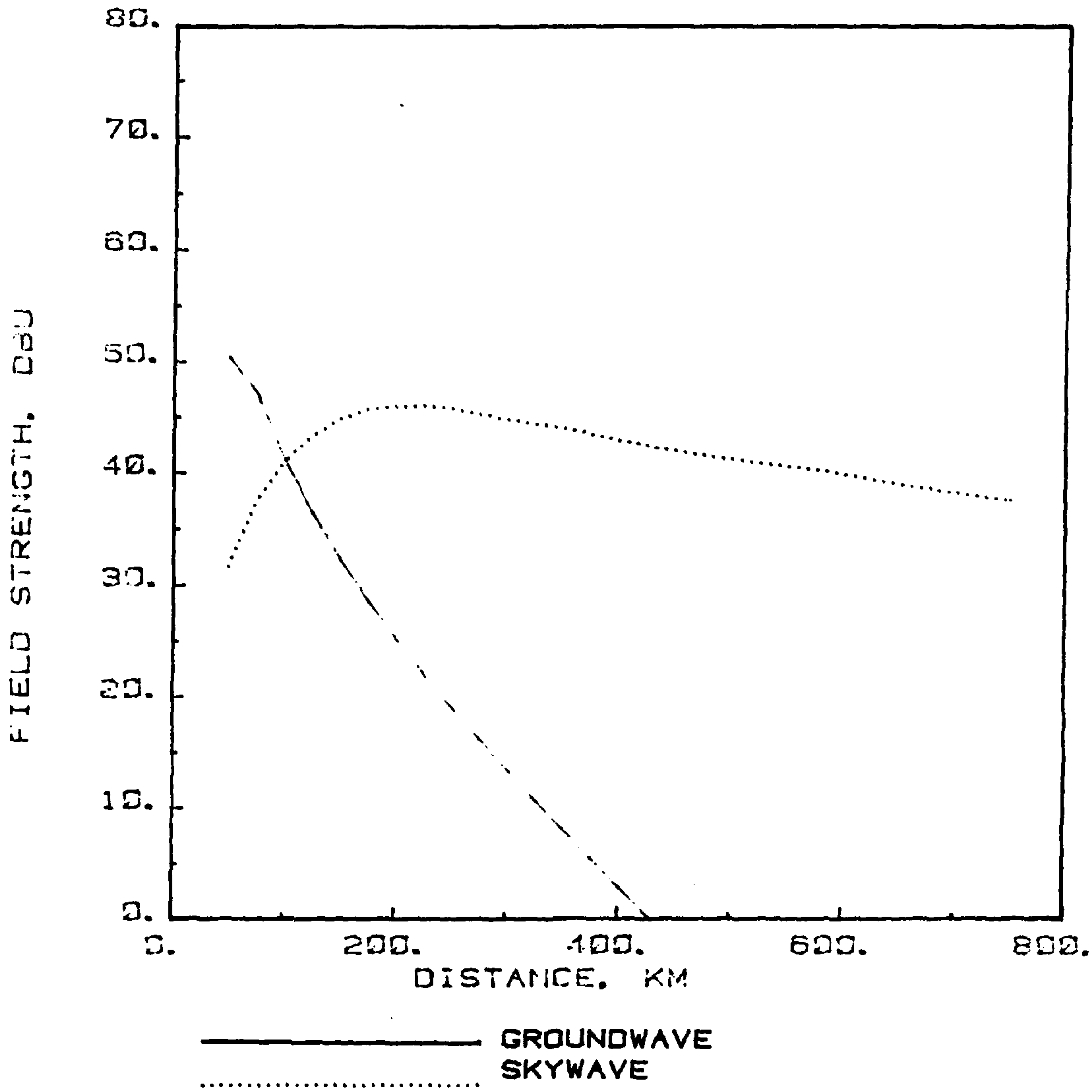

Figure 11. Groundwave and skywave components of the field strength as a function of distance for 1000 kHz over land paths.

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